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GROSS STATIC LIFTING CAPACITY OF LOGGING BALLOONS

by

Ward W. Carson, *Mechanical Engineer*

and

Penn A. Peters, *Aerospace Engineer*

ABSTRACT

Logging balloons, in a range of sizes, are operated in a variety of atmospheric conditions. The influence of these conditions upon the gross static lifting capacity of the balloon can be computed from the fundamental principles of aerostatics and thermodynamics. This research paper discusses the parameters influencing static lift and shows how it can be computed. Nomographs are provided for field computation of gross static lift from values of pressure, temperature, and volume. This information may be used by the balloon logger as he studies his balloon performance and monitors gas loss during operation.

Keywords: Balloon logging, aerial logging, logging, logging equipment.

NOMENCLATURE

Symbol		Abbreviation of unit of measure
L	Gross static lift	lb.
p	Pressure	lb./ft.^{2}
p_D	Design pressure, lowest pressure expected during balloon operation	lb./ft.^{2}
p_v	Partial pressure of the water vapor	lb./ft.^{2}
p_w	Vapor pressure corresponding to the wet-bulb temperature	lb./ft.^{2}
R	Perfect gas constant	(ft.-lb./lb.-°R)
T	Temperature	°R or °F.
T_d	Dry-bulb temperature	°F.
T_D	Design temperature, highest gas temperature expected during balloon operation	°R or °F.
T_w	Wet-bulb temperature	°F.
V_D	Design volume of the balloon, volume occupied by lifting gas when the balloon is fully inflated	ft.^{3}
V_g	Volume of lifting gas contained in the balloon	ft.^{3}
V_{STD}	Volume occupied by lifting gas at standard conditions of temperature and pressure	ft.^{3}
w	Density	lb./ft.^{3}
W_g	Weight of lifting gas	lb.
a	Air	
g	Lifting gas	
m	Mixture of dry air and water vapor	

1.0 INTRODUCTION

Fundamental to design and operation of the logging balloon is determination of its gross static lift capability and how lift is influenced by size, lifting gas properties, and atmospheric environment. These are static considerations which ignore the effects of the dynamics and aerodynamics of operation. Although dynamics and aerodynamics must be considered in a complete design of the logging balloon, only static lift considerations are discussed in this paper.

Ability to compute static lift is required of the balloon logger for several reasons. Possibly the most obvious requirement for this knowledge is for predicting the change in lifting potential of a given balloon as it moves from one operation to another. As environmental conditions are then changed, the influence upon the balloon static lift potential could become an important design consideration. Accurate knowledge of static lift also becomes necessary in a program for monitoring gas loss. A nearly constant rate of gas loss is expected in most balloons due to natural diffusion through the fabric. Additional loss through holes or other damage points in the balloon will increase this loss. Monitoring the gas loss by periodic measurement of net lift and performing the calculations discussed in this paper can aid in early detection of additional loss through holes. An example is included to describe this procedure.

2.0 LIFTING GASES

Several gases are available for balloon inflation, each with its advantages and disadvantages. The single requirement is that the gas be much lighter than air or can be made so with a moderate amount of heating. The commonly used lifting gases and their properties are listed in table 1.

Hydrogen, the lightest of all gases, is highly flammable over a wide range of concentrations in air. Accidents with hydrogen have made designers and users leery of its application.

Helium, the next lightest gas, has the attractive feature of being completely inert. Despite its high cost, helium has generally been considered the most suitable gas for a logging balloon.

Ammonia lacks the lifting potential of helium or hydrogen but is attractive from the standpoint of availability and cost. Ammonia is an inexpensive gas which can be generated from anhydrous ammonia on site for inflation of a logging balloon. However, it is incompatible with conventional balloon fabrics[1] and glues and has relatively high density.

[1] Hilton H. Lysons. Compatibility of balloon fabrics with ammonia. Pac. Northwest Forest & Range Exp. Sta. USDA Forest Serv. Res. Note PNW-42, 9 p., illus., 1966.

Table 1.—*Gas properties at 68° F. and standard atmospheric pressure*

Property	Hydrogen	Helium	Ammonia	Air
Molecular weight	2.0	4.0	17.0	29.0
Density, $\frac{\text{lb.}}{\text{ft.}^3}$	0.00523	0.0104	0.0442	0.0753
Density relative to air	0.0695	0.138	0.587	1.0
Gas constant, $\frac{\text{ft.-lb.}}{\text{lb.-}^\circ\text{R}}$	766.8	386.3	90.77	53.3
Specific heat, $\frac{\text{B.t.u.}}{\text{lb.-}^\circ\text{R}}$	3.42	1.25	0.523	0.241
Gross lift per 1,000 cubic feet, lb.	70.7	64.9	31.1	–

Hot air has advantages of availability, cost, stability, and compatibility with fabrics but the one serious disadvantage of requiring a heat source. Experience with hot air balloons indicates the energy requirement for a logging balloon would range in the millions of B.t.u.'s per hour. The operation and fuel requirements of such a configuration can be readily seen to present major problems in the woods.

3.0 GROSS STATIC LIFT

That portion of a logging balloon's total lift attributable to its buoyancy is referred to as static lift. The upward force, or buoyant force, equals the weight of the volume of air displaced by the balloon. Reducing the buoyant force by the weight of gas in the balloon yields the gross static lift. The gross static lift of the balloon is given by

$$L = (w_a - w_g)V_g.$$

The net upward force acting on the balloon tether line equals the gross static lift of the balloon less the constant tare of bag, support lines, tether line, safety line, etc. Gross static lift, on the other hand, may vary considerably with changes in atmospheric conditions. The following discussion is restricted to the factors affecting the gross static lift of the balloon. The balloon's environment is considered at rest, and pressures, temperatures, and densities discussed are taken as static values.

3.1 Balloon Type

The balloon type found most useful for logging applications is the flabby balloon, constructed with a ballonet section. A cross section of a typical balloon is shown in figure 1. One desirable feature of this design is that gross static lift is almost independent of ambient conditions since gas volume expands or contracts in response to atmospheric pressure and temperature changes.

The normal operating mode of the flabby balloon is the partially inflated condition. In this condition, lift of the balloon will not vary with atmospheric changes in temperature and pressure, providing gas temperature inside the balloon is the same as outside air temperature. The technical discussion supporting this is presented in Appendix A.

Figure 1.—Flabby balloon with ballonet: *A*, Partially inflated; *B*, fully inflated.

Figure 1B shows the balloon in fully inflated condition. For purposes of discussion, volume in the bag when fully inflated will be called the design volume of the balloon. Once gas has expanded to design volume, additional expansion will either pressurize the gas or force gas out of the balloon. Many flabby balloons are equipped with pressure relief valves to prevent rupture. It is good operating practice to initially underinflate the balloon to accommodate gas expansion expected during the balloon's operation.

It will be assumed in the discussion to follow that initially the balloon was underinflated enough to prevent gas expansion beyond the design volume of the balloon. Therefore, volume of gas is always less than or just equal to design volume.

3.2 Atmospheric Pressure and Temperature Effects

A derivation of equations expressing influence of pressure and temperature is presented in Appendix A. It is shown that dependence of static lift upon pressure can be expressed as a function of the ratio of balloon gas pressure to balloon ambient air pressure. For a flabby balloon, pressure of the gas in essentially the same as atmospheric pressure, and the pressure ratio is always equal to unity. Therefore, for a balloon containing a given amount of gas, gross static lift does not depend upon atmospheric pressure. Gas pressure adjusts to external air pressure, and gas volume

changes accordingly. As long as the gas volume does not exceed the design volume of the balloon, changes in volume occur naturally with changes in pressure such that there is no change in gross static lift.

Dependence of gross static lift on temperature is similar to the pressure dependence; i.e., lift depends on the ratio of temperature of gas to temperature of air. It is useful when discussing the effects of temperature on lift to use the term "superheat." Superheat is equal to gas temperature minus air temperature. When gas temperature and air temperature are equal (zero superheat), lift is independent of temperature. The condition of no superheat is the exception rather than the rule. The normal operating condition is one of positive superheat; i.e., the temperature of gas is greater than temperature of air. The temperature of gas in the balloon will rise until the heat input from solar radiation is balanced by heat loss due to convection. Convection heat loss is directly proportional to superheat. Heat input from solar radiation is greatest for clear, sunny days. Therefore, on clear, sunny days the balloon lift is greater due to the greater amount of superheat required to balance the solar radiation heat input to the balloon. Since the superheat condition is more pronounced on sunny days, the variation in lift has sometimes been incorrectly attributed to atmospheric temperature changes.

Accurate prediction of the amount of superheat that a balloon will experience during its operating life is important to the balloon operator. Overestimating the potential amount of superheat will cause a loss in load-carrying capacity because the balloon is not initially inflated to capacity. Underestimating the amount of superheat may require dumping helium overboard to prevent overpressurizing the balloon at extreme operating conditions. Although methods are available to compute approximations[2] of superheat which depend upon balloon volume, material, shape, and atmospheric conditions, they are beyond the scope of this paper. Direct measurement of balloon gas temperature would be the most practical means of assessing the superheat.

3.3 Humidity

Humidity variations in the atmosphere affect lift in two ways. First, gross static lift is slightly less on a humid day because density of humid air is less than density of dry air. The percent change in gross static lift due to this effect is discussed in Appendix B.

A second effect of humidity is to add a variable tare weight to the balloon by condensation. A coat of dew may add over 1,000 pounds of weight on a 500,000-cubic-foot balloon. The condensation is most troublesome when comparing successive static lift measurements to monitor gas loss. Since corrections to lift measurements for effect of condensation would be subject to large errors, the best approach is to avoid taking lift measurements when condensation can be seen on the bag.

3.4 Purity

Gross static lift is directly proportional to purity of lifting gas. Lifting gas is generally delivered nearly 100 percent pure; however, air can be expected to diffuse into the balloon during inflation and operation. For example, a balloon containing 95 percent by volume pure helium generates 95 percent of the lift of the same balloon containing 100 percent of pure helium.

4.0 CALCULATIONS OF BALLOON STATIC PERFORMANCE

A series of examples are presented to demonstrate procedures for determining balloon requirements and characteristics. These calculations all depend upon equations presented in Appendix A. Although the equations of Appendix A require relatively simple calculations, need for a calculator or slide rule can require a cumbersome computing routine for in-field application. To simplify the operation, nomographs have been included in this paper. A nomograph is a convenient device frequently used to represent an equation and to avoid arithmetic computations. The

[2] E. R. G. Eckert and Robert M. Drake, Jr. Heat and mass transfer. New York, McGraw-Hill, 530 p., illus., 1959.

nomographs of this paper provide means to compute air density, gas density (fig. 2), and gross static lift per pound of gas (fig. 3) for the range of pressures and temperatures occurring in balloon logging. These nomographs have been prepared for helium since it is presently the usual lifting gas for logging balloons.

4.1 Initial Inflation Requirements

Problem statement: What is the initial inflation requirement and expected gross static lift for a helium-filled balloon operating in a given environment? The expected operating conditions are a maximum pressure altitude[3] of 5,000 feet and a high in air temperature of 80° F. In addition, 40° F. of superheat is expected at maximum temperature.

Problem solution: The density nomograph can be used to determine the inflation requirements of the balloon. With inputs of pressure altitude and gas temperature, including superheat, gas density in pounds per cubic foot can be determined. The product of density and initial inflation volume of the balloon will establish the amount of helium required. Assuming the balloon is to be filled to a design volume of 250,000 cubic feet, the solution would proceed as follows.

Figure 4 determines a balloon gas density of 0.00786 pounds per cubic foot from the expected operating conditions of 5,000 feet pressure altitude and 120° F. gas temperature. At this density, the weight of helium in a 250,000-cubic–foot balloon would be

$$(250{,}000)\ (0.00786) = 1{,}965 \text{ pounds.}$$

If the helium requirements are desired in standard cubic feet, as normally delivered by the compressed-gas industry, the value must be referenced to their standard conditions[4] of pressure and temperature. If standard conditions of temperature 32° F. and pressure 29.92 inches of mercury are assumed, the standard density of helium is 0.01113 pounds per cubic foot. The cubic feet required at these standard conditions in the example above becomes

$$V_{STD} = \frac{w}{w_{STD}}\ V = \frac{0.00786}{0.01113}(250{,}000) =$$
$$176{,}550 \text{ cubic feet.}$$

The second part of the problem—determination of expected gross static lift—uses the lift nomograph for solution (fig. 5). This nomograph determines gross static lift per pound of gas which depends upon gas and air temperatures only. For this example, the result is 6.78 pounds of lift per pound of helium. Since the balloon is expected to contain 1,965 pounds of helium, the gross static lift would be

$$L = (6.78)\ (1{,}965) = 13{,}317 \text{ pounds of lift.}$$

If the balloon is not in the superheat condition, a lift of 6.25 pounds per pound of helium is determined from the nomograph. This gives a lift of

$$L = (6.25)\ (1{,}965) = 12{,}281 \text{ pounds of lift.}$$

4.2 Balloon Relocation

Problem statement: A 250,000-cubic-foot (design volume) balloon containing 1,965 pounds of helium is to be moved in its inflated condition to a new logging site. The extreme operating conditions of the new site are:

Pressure altitude	8,000 feet
Expected maximum gas temperature	100° F.
Expected maximum air temperature	80° F.

[3]Pressure altitude is the reading of an altimeter when adjusted to the standard sea-level atmospheric pressure of 29.98 inches of mercury. Since it reflects the ambient temperature and atmospheric pressure, pressure altitude may not correspond to the actual elevation.

[4]Goodyear Aerospace Corporation. Tethered balloon handbook. Final report, May 1968-December 1968, 221 p., illus.

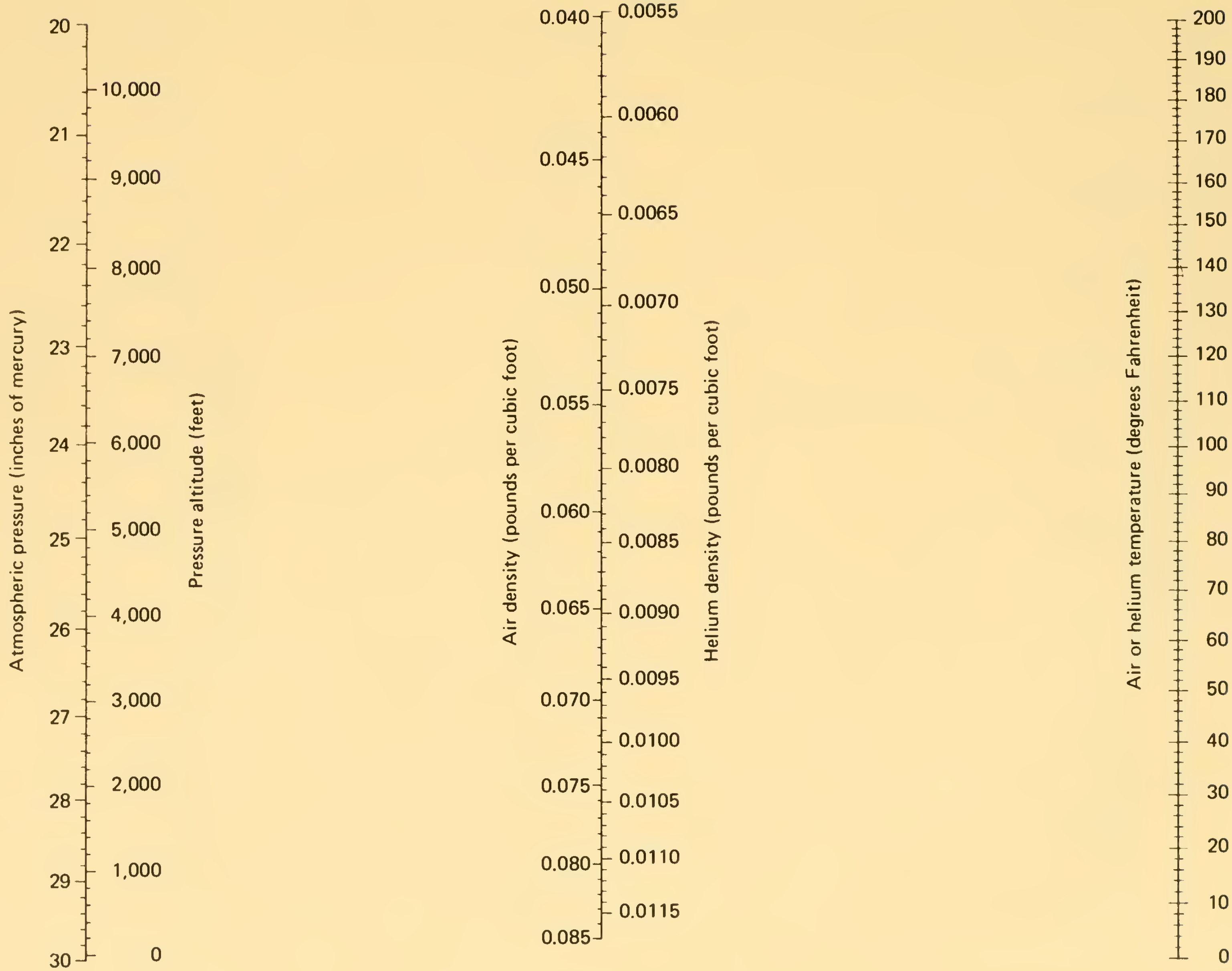

Figure 2.—Density nomograph.

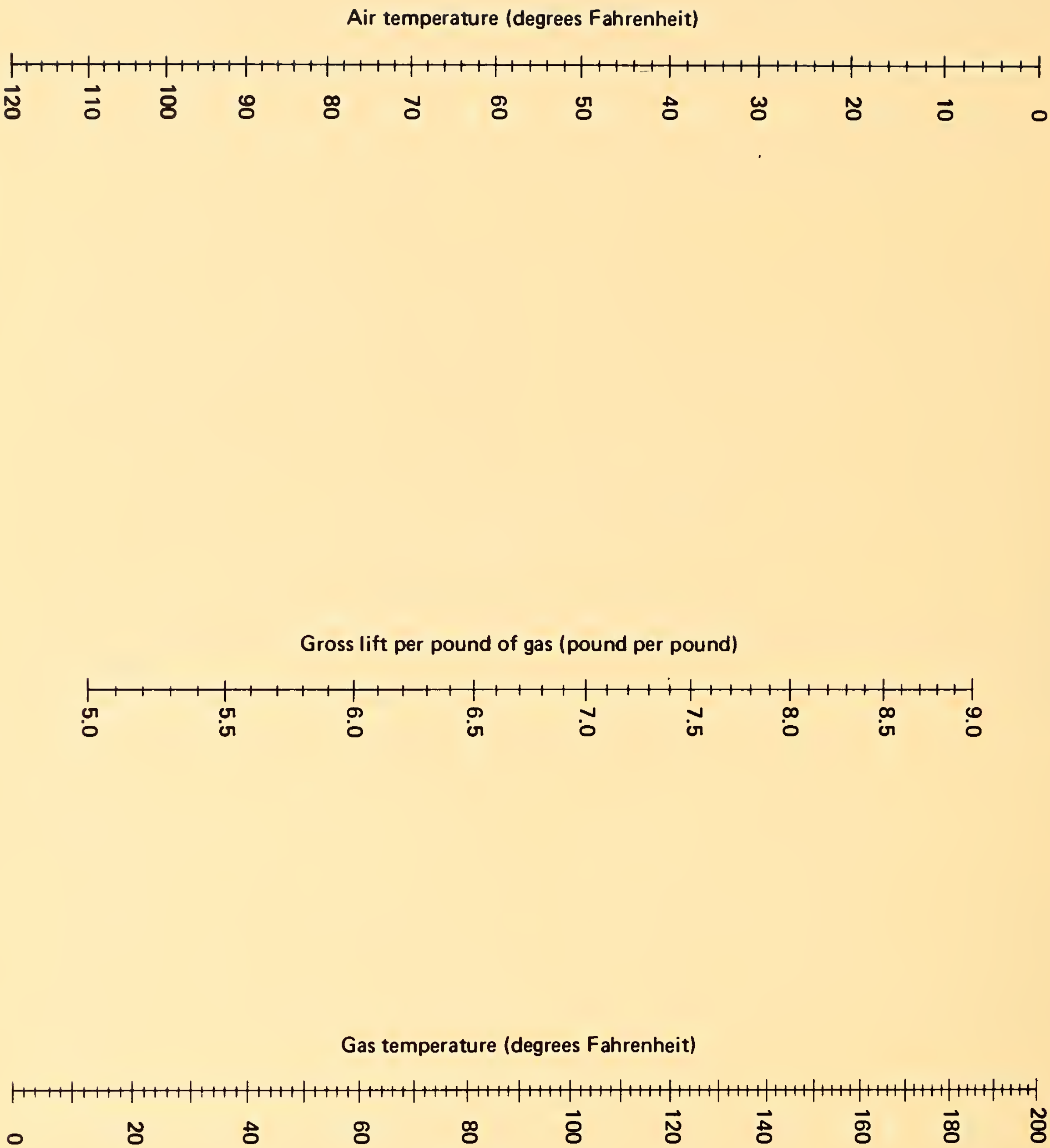

Figure 3.—Lift nomograph.

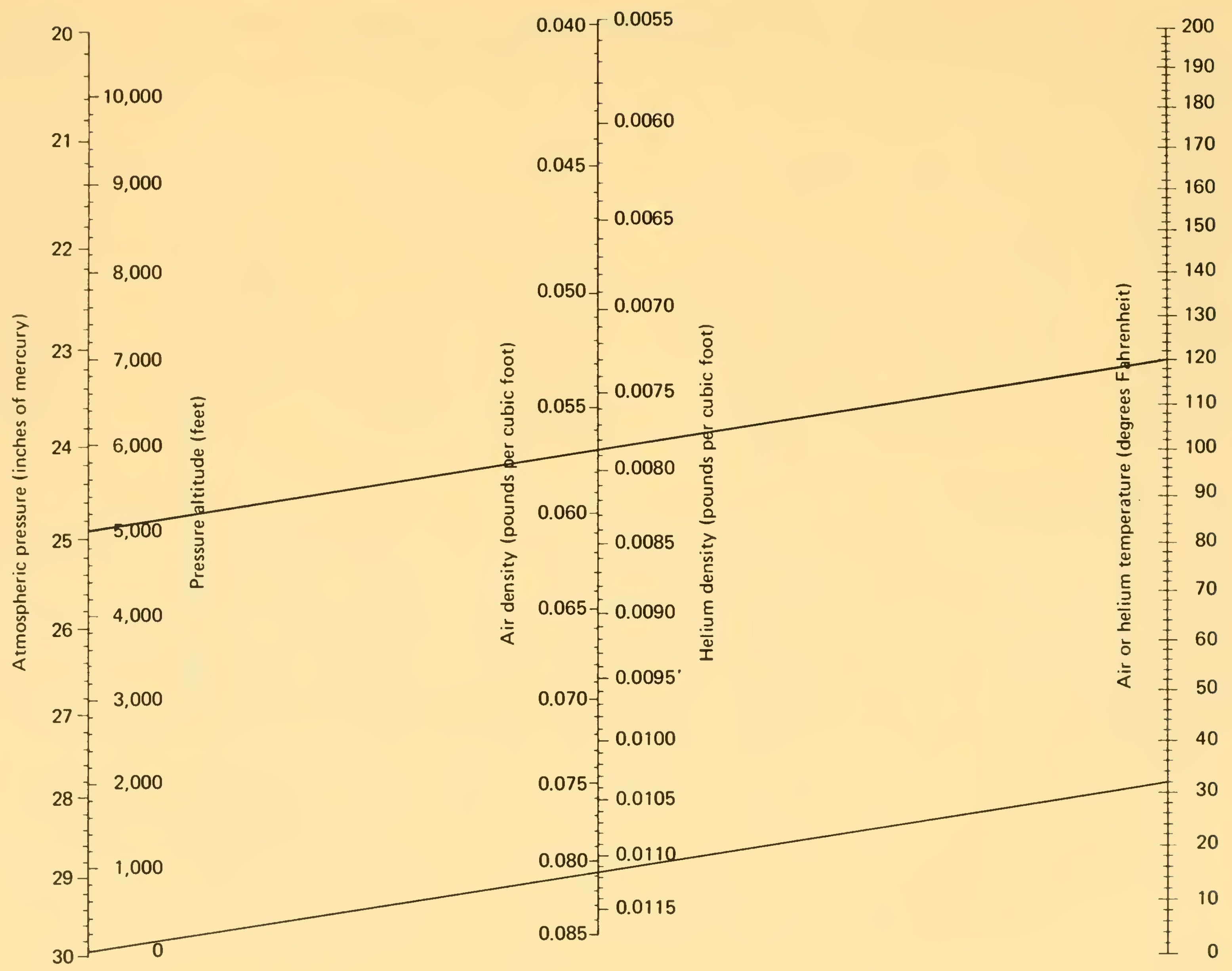

Figure 4.—Nomograph for determining initial inflation requirements.

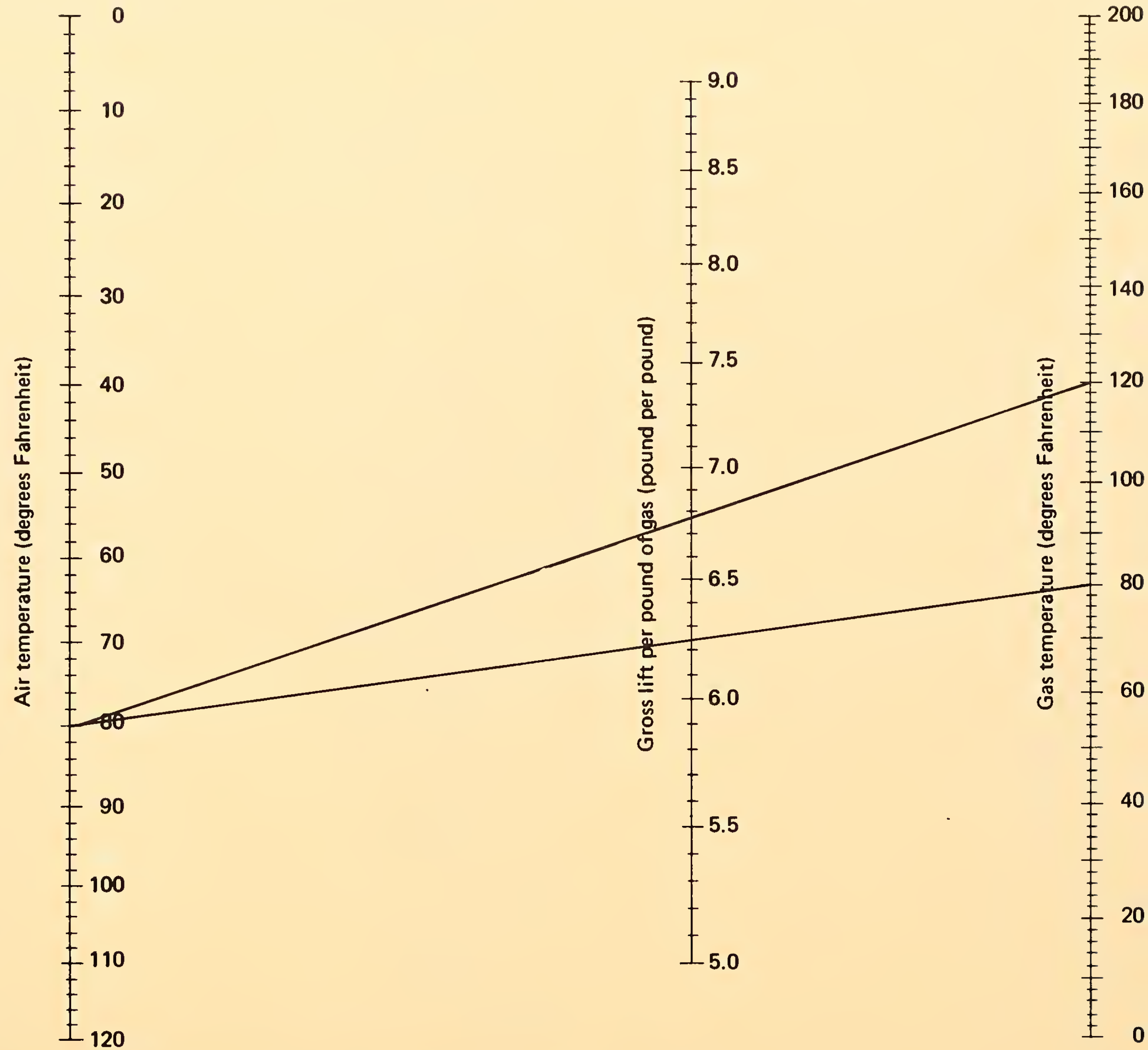

Figure 5.—Nomograph for determining initial inflation requirements.

Will the balloon be overpressurized if relocated to these operating conditions? If so, how much helium should be removed, and what is the associated loss in lift at the zero superheat condition?

Problem solution: If 1,965 pounds of helium occupies the 250,000 cubic feet of balloon capacity, the gas would have a density of 0.00786 pound per cubic foot. If this gas was at the anticipated extreme gas temperature of 100° F., the nomograph of figure 6 indicates gas would be at a pressure of 24.04 inches of mercury. This is higher than 22.23 inches of mercury, which is the atmospheric pressure corresponding to 8,000 feet pressure altitude. This means that gas pressure inside the balloon would exceed atmospheric pressure and could lead to structural failure of the balloon. If a pressure relief valve was provided, it would open, releasing sufficient helium to maintain pressure inside the balloon within allowable limits.[5]

When helium is dumped intentionally before moving or through a relief valve while moving, the weight of gas which remains in the balloon can be computed. The conditions of 8,000 feet pressure altitude and 100° F. gas temperature are used to determine expected gas density at the new site. Figure 6 shows this to be 0.00727 pound per cubic foot. If the balloon is filled to the 250,000-cubic-foot volume at this density, weight of gas contained would be

$$W_g = (0.00727)(250{,}000) = 1{,}817 \text{ pounds of helium.}$$

This indicates that 148.0 pounds of gas would have to be removed or would be lost in moving to the new site.

[5] Pressure in the balloon will be greater than atmospheric pressure since relief valves are activated by a slight overpressure. In calculations of gas loss through valves, however, assumption of equal pressures inside and outside the bag is made. This assumption yields a slightly conservative estimate for gas loss.

4.3 Monitoring Gas Loss

Consecutive sets of lift measurements are taken for the purpose of monitoring gas loss. In addition to net lift, the following data are required to calculate weight of helium contained in the balloon: gas temperature, atmospheric temperature, tare, and holddown geometry. Gas weight calculations are illustrated by the following example:

Measured and known quantities:

Net lift measured in tether line	10,000 pounds
Air temperature around balloon	60° F.
Helium temperature in balloon	60° F.
Known tare for this balloon	3,500 pounds

Figure 7 shows how gas and air temperatures determine gross lift per weight of gas. This lift, 6.25 pounds per pound of gas, and the gross static lift of 13,500 pounds (net lift plus tare weight) indicate the balloon contains

$$W_g = \frac{13{,}500 \text{ pounds}}{6.25 \text{ pounds per pound}} = 2{,}160 \text{ pounds of helium.}$$

Similar data, taken at periodic intervals, could be used to monitor the amount of helium contained in the balloon. Such a collection of data is plotted in figure 8. The observer will notice some scatter in these data due to errors in measurement and uncertainties in helium purity, humidity, relative wind, condensation on the balloon, and holddown geometry. However, reliable trends can be developed as these errors should average, and trends are most important to the balloon operator. A gradual decrease in the curve may indicate a slow leak, or a sharp drop may indicate that a more serious condition exists. A record of makeup gas required can also be facilitated with figure 8.

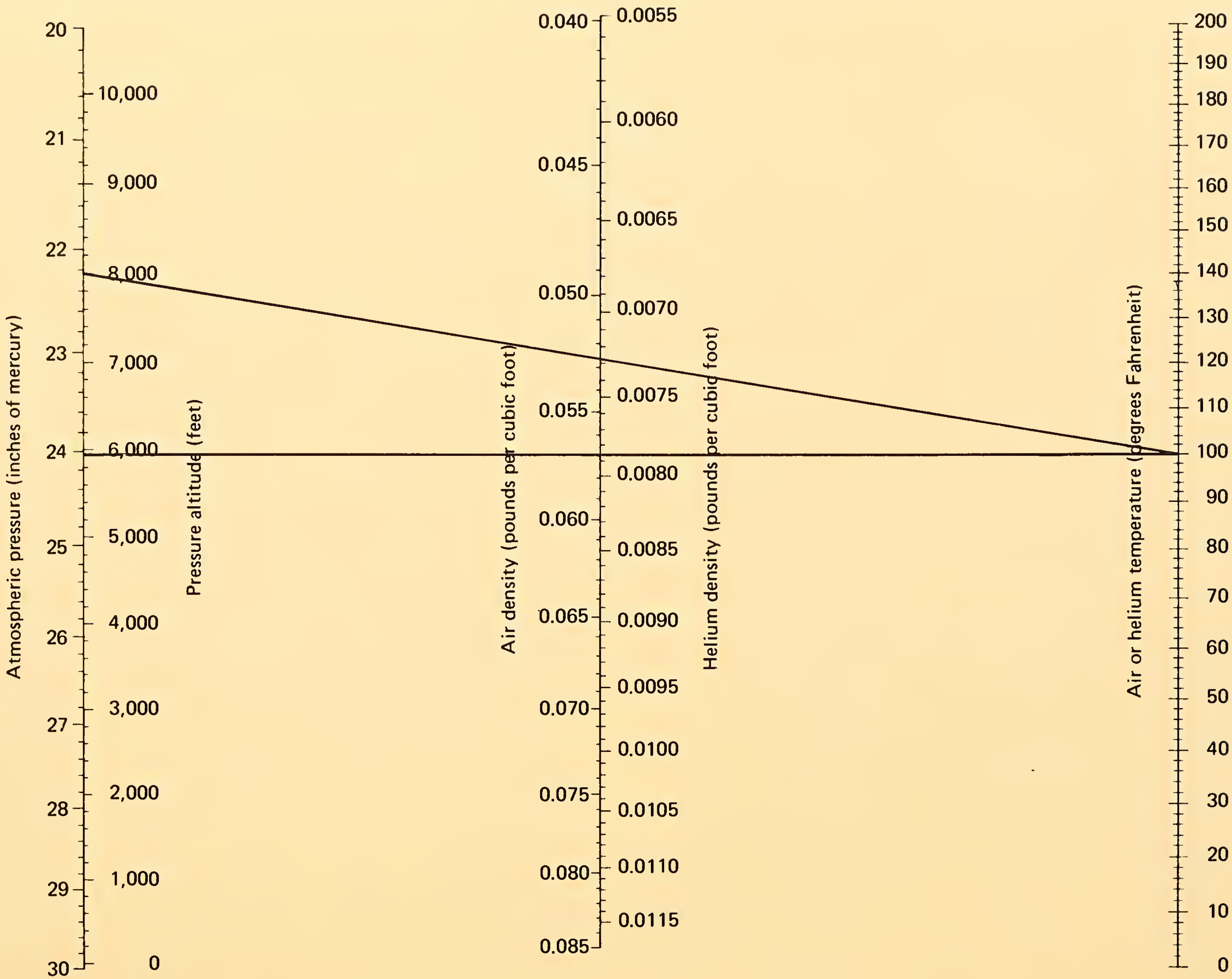

Figure 6.—Nomograph for balloon relocation analysis.

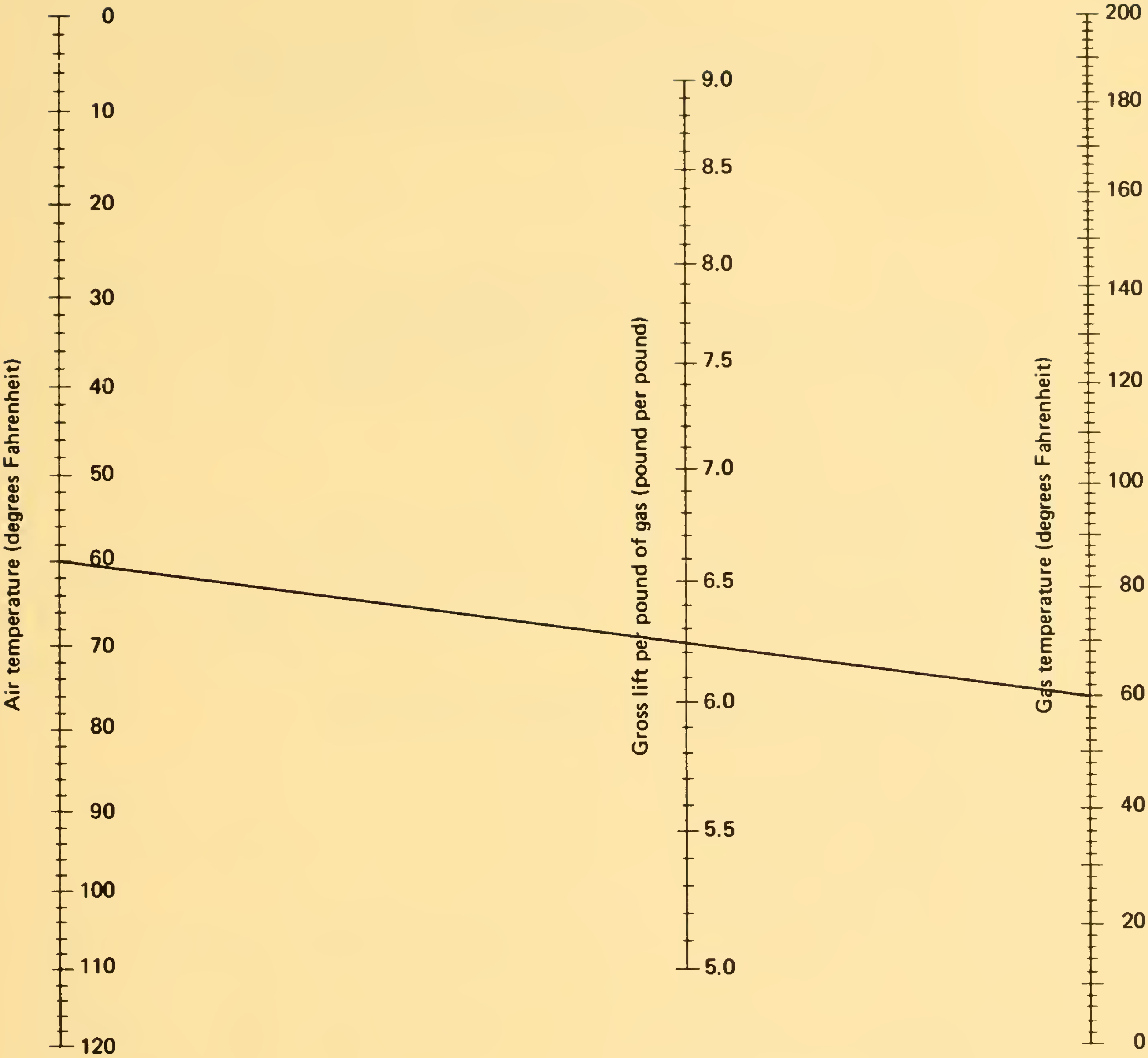

Figure 7.—Nomograph for monitoring gas loss.

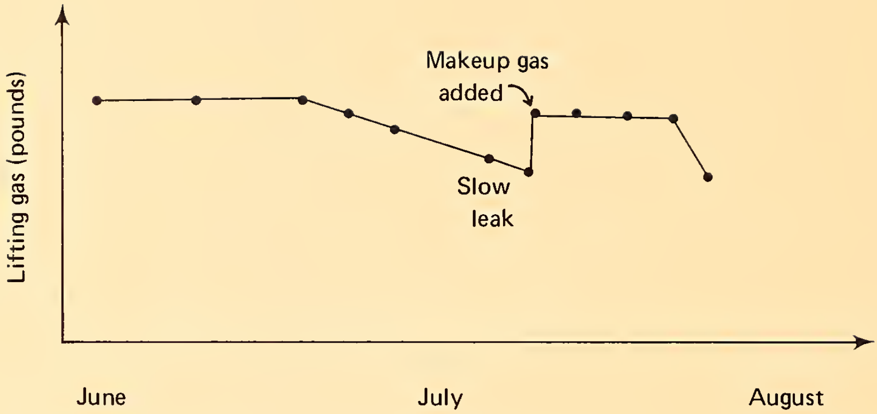

Figure 8.—Record of lifting gas stored in balloon.

APPENDIX A

GROSS STATIC LIFT AS AFFECTED BY PRESSURE, TEMPERATURE, AND LIFTING GAS VOLUME

Lift of a lighter-than-air balloon can be calculated from the principle of buoyancy. Gross upward lift experienced by the balloon is equal to weight of displaced air less weight of an equal volume of lifting gas. In algebraic terms, we have

$$L = (w_a - w_g)V_g. \qquad (1)$$

To predict effects of pressure and temperature changes on lift, pressure and temperature have to be related to weight of air and lifting gas by the equation of state. Both air and lifting gas can be considered as ideal gases. Their respective equations of state are

$$p_A = w_a R_a T_a$$

and

$$p_g = \frac{W_g R_g T_g}{V_g} = w_g R_g T_g. \qquad (2)$$

Mass of gas used to initially inflate the balloon is determined by requiring, during inflation, that the lifting gas expand to fill the balloon at the extreme pressures and temperatures to be encountered during the logging operation. We can use equation 2 to state this requirement analytically.

$$V_g = \frac{W_g R_g T_g}{p_g} \leq V_D \text{ for all } T_g \text{ and } p_g. \qquad (3)$$

Equation 3 states that at all operating conditions of pressure and temperature, volume occupied by the lifting gas has to be less than or equal to design volume of the balloon.

Therefore, the amount of lifting gas used to initially inflate the balloon (takeoff inflation) is given by

$$W_g = \frac{p_D V_D}{R_g T_D}. \qquad (4)$$

Where,

V_D = gas volume with fully extended ballonet, a design parameter of the balloon,

R_g = perfect gas constant of the lifting gas, property of the lifting gas,

p_D = lowest pressure experienced by the lifting gas during operation. Since the pressure inside the balloon in a still air environment is the same as the pressure outside the balloon, this is numerically the same as the lowest atmospheric pressure during operation,

T_D = highest absolute temperature experienced by the lifting gas during operation. This will be higher than the highest atmospheric temperature expected since the normal operating condition will be one of positive superheat.

Using this information and the equations of state, we can obtain an expression for the gross lift of a balloon in terms of pressure and temperature

$$L = W_g \left(\frac{p_a R_g T_g}{p_g R_a T_a} - 1\right). \qquad (5)$$

Applying the boundary condition that the pressure is the same inside and outside the balloon (that is, $p_a = p_g$), we have the following important result,

$$L = W_g \left(\frac{R_g T_g}{R_a T_a} - 1\right). \qquad (6)$$

The atmospheric pressure exerted on the balloon will change with local weather conditions or changes in altitude; however, the

lift, L, experienced by the balloon will not change with air pressure changes. This is algebraically expressed by equation 6.

The effect of initial inflation is clearly demonstrated in equation 6. Since lift is directly proportional to the weight of lifting gas, the object is to put in as much gas as possible without overinflating the balloon. The correct amount of initial gas is given by equation 4. Overinflation will result in loss of inflation gas at extreme operating conditions of pressure and temperature, with a consequent loss in lift capability and financial loss.

The effect of temperature is shown in equation 6. The gross lift is constant as long as the gas temperature inside the balloon is the same as the air temperature outside. This is not the usual situation, however. Normally, $T_g > T_a$, and the lift is increased as the gas temperature increases over the air temperature. The superheat is greater on warm days with clear skies, accounting for the observations of increased lift under such conditions.

APPENDIX B

EFFECTS OF HUMIDITY

Moist air is a mixture of water vapor and dry air; and since both are perfect gases, moist air is a perfect gas. The following equations of state apply to these perfect gases:

$p_m = w_m R_m T_m$ for an atmosphere of dry air and water vapor mixture;

also,

$p_a = w_a R_a T_a$ for dry air

and

$p_v = w_v R_v T_v$ for water vapor. (1)

The perfect gas constant for the air-vapor mixture can be related to the gas constants for air and vapor, respectively. Dalton's law states the total pressure of a mixture of gases is equal to the sum of the partial pressures of the constituents when each constituent occupies the volume of the mixture at the same temperature as that of the mixture. A mathematical statement of Dalton's law is

$$p_m = p_a + p_v$$
$$w_m = w_a + w_v$$
$$T_m = T_a = T_v. \qquad (2)$$

Combining equations 1 and 2, and using $\frac{R_a}{R_v} = 0.622$, we arrive at the following,

$$R_m = R_a \frac{p_m}{p_m - 0.378\, p_v} \quad \frac{\text{ft.-lb.}}{\text{lb.-}^\circ\text{R}} \qquad (3)$$

Equation 3 allows calculation of the perfect gas constant for any air-water vapor mixture, provided the total pressure of the mixture (barometric pressure) and the partial pressure of the water vapor are known. The vapor pressure is not directly measurable; however, it can be determined with a semiempirical expression giving the vapor pressure as a function of measurable quantities, namely

$$p_v = p_w - \frac{(p_m - p_w)(T_d - T_w)}{2{,}800 - 1.3\, T_w}. \qquad (4)$$

The dry-bulb and wet-bulb temperatures can be measured with a sling psychrometer. The vapor pressure corresponding to the wet-bulb temperature can be read from steam tables. The temperatures should be expressed in degrees Fahrenheit for use in the formula.

The gross static lift of a balloon in humid air is

$$L\,(\text{moist air}) = W_g\,(\frac{R_g T_g}{R_m T_a} - 1). \qquad (5)$$

The gross static lift in dry air is

$$L\,(\text{dry air}) = W_g\,(\frac{R_g T_g}{R_a T_a} - 1). \qquad (6)$$

We can see from equation 3 that R_m is always greater than or equal to R_a. Therefore, the balloon lift in humid air is always less than or equal to the lift in dry air. Table 2 shows the effect of humidity on lift. This effect is second-order and not worth making corrections for in-field calculations.

Table 2.—*Comparison of static lift in dry and saturated air*[1]

Atmospheric temperature	Vapor pressure	Lift in dry air	Lift in saturated air	Loss in lift
	Pounds per square inch	*Pounds*	*Pounds*	*Percent*
0° F.	0.018	12,500	12,493	0.06
10° F.	.031	12,500	12,488	.10
20° F.	.052	12,500	12,480	.16
30° F.	.084	12,500	12,470	.24
40° F.	.121	12,500	12,450	.40
50° F.	.178	12,500	12,430	.56
60° F.	.256	12,500	12,400	.80
70° F.	.363	12,500	12,360	1.12
80° F.	.507	12,500	12,310	1.52
90° F.	.698	12,500	12,240	2.08

[1] Conditions are: atmospheric pressure = 14.7 pounds per square inch; lifting gas—pure helium, 2,000 pounds or 179,500 cubic feet (32° F.), 14.7 pounds per square inch; and no superheat.

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